

VU Research Portal

Turn up the bass!

van Heijningen, J.V.

2018

document version

Publisher's PDF, also known as Version of record

[Link to publication in VU Research Portal](#)

citation for published version (APA)

van Heijningen, J. V. (2018). *Turn up the bass! Low-frequency performance improvement of seismic attenuation systems and vibration sensors for next generation gravitational wave detectors*. [PhD-Thesis - Research and graduation internal, Vrije Universiteit Amsterdam].

General rights

Copyright and moral rights for the publications made accessible in the public portal are retained by the authors and/or other copyright owners and it is a condition of accessing publications that users recognise and abide by the legal requirements associated with these rights.

- Users may download and print one copy of any publication from the public portal for the purpose of private study or research.
- You may not further distribute the material or use it for any profit-making activity or commercial gain
- You may freely distribute the URL identifying the publication in the public portal ?

Take down policy

If you believe that this document breaches copyright please contact us providing details, and we will remove access to the work immediately and investigate your claim.

E-mail address:

vuresearchportal.ub@vu.nl

Contents

| | |
|--|--------------|
| Abstract | xi |
| Acknowledgments | xv |
| List of tables | xviii |
| List of figures | xx |
| Introduction | 1 |
| Chapter guideline | 4 |
| 1 Context and theoretical aspects | 7 |
| 1.1 General relativity and gravitational waves | 8 |
| 1.1.1 Linearized general relativity | 8 |
| 1.1.2 Gravitational waves | 9 |
| 1.1.3 Sources of gravitational waves | 11 |

| | |
|---|----|
| 1.2 Gravitational wave detections | 14 |
| 1.2.1 First detection of gravitational waves | 14 |
| 1.2.2 Other LIGO detections in O1 and O2 | 15 |
| 1.2.3 First triple-coincident detection by LIGO and Virgo | 19 |
| 1.2.4 First observation of a binary neutron star inspiral | 21 |
| 1.3 Vibration isolation | 23 |
| 1.3.1 Damped harmonic oscillators | 23 |
| 1.3.2 Seismic attenuation system components | 26 |
| 1.4 Controls | 32 |
| 1.4.1 Feedback | 33 |
| 1.4.2 Control of a single degree of freedom | 34 |
| 1.4.3 Digital and modern control | 36 |
| 1.5 Sensing | 37 |
| 1.5.1 Vibration sensors | 38 |
| 1.5.2 Sensors for gravitational wave detectors | 39 |
| 2 Gravitational wave detectors | 43 |
| 2.1 Interferometric detectors | 44 |
| 2.1.1 Measuring a space-time perturbation | 45 |
| 2.1.2 Interferometry in practice | 47 |
| 2.2 Sensitivity improvements | 50 |
| 2.2.1 Sensitivity limitations | 54 |
| 2.2.2 Readout methods | 59 |
| 2.3 Advanced Virgo | 62 |

| | |
|--|-----------|
| 2.3.1 From Virgo+ to Advanced Virgo | 63 |
| 2.3.2 Strain sensitivity of Advanced Virgo | 68 |
| 2.3.3 Global network | 71 |
| 2.4 Future detectors | 72 |
| 2.4.1 Einstein Telescope | 73 |
| 2.4.2 LISA | 76 |
| 3 Multi-stage seismic attenuation system | 79 |
| 3.1 Auxiliary optics on suspended benches | 80 |
| 3.1.1 Angular modes of core optics | 80 |
| 3.1.2 Sensing of the suspended end benches | 81 |
| 3.2 MultiSAS characterization | 83 |
| 3.2.1 Requirements on the transfer function | 85 |
| 3.2.2 Transfer function measurements | 86 |
| 3.2.3 Inverted pendulum leg parallelism | 89 |
| 3.2.4 Thermal shields | 90 |
| 3.2.5 Acoustic coupling | 93 |
| 3.3 Design of the control system | 95 |
| 3.3.1 Top stage control | 96 |
| 3.3.2 Signal blending | 98 |
| 3.3.3 Vertical ground subtraction | 101 |
| 3.3.4 Suspended bench control | 102 |
| 3.4 Commissioning for Advanced Virgo | 105 |
| 3.4.1 MultiSAS performance at Advanced Virgo | 105 |

| | | |
|----------|---|------------|
| 3.4.2 | GAS blade failure | 108 |
| 3.4.3 | Scattered light | 112 |
| 4 | Femtometer precision sensing | 115 |
| 4.1 | Monolithic accelerometer design | 117 |
| 4.1.1 | Mechanical modeling | 117 |
| 4.1.2 | Proof mass suspension thermal noise | 119 |
| 4.2 | Interferometric readout | 121 |
| 4.2.1 | Readout circuit | 122 |
| 4.2.2 | Noise budget | 124 |
| 4.2.3 | Sensor characterisation | 126 |
| 4.3 | Increasing the dynamic range | 131 |
| 4.3.1 | Using a piezo as actuator | 131 |
| 4.3.2 | Using a voice coil as actuator | 135 |
| 4.3.3 | Noise measurement in the MultiSAS test facility | 136 |
| 5 | Control of KAGRA suspension prototypes | 141 |
| 5.1 | KAGRA vibration isolation | 143 |
| 5.1.1 | Suspensions overview | 144 |
| 5.1.2 | Type A and type B(p) suspensions | 145 |
| 5.2 | Inverted pendulum stage control | 146 |
| 5.2.1 | LVDT read out monolithic accelerometers | 147 |
| 5.2.2 | Pre-isolator stage simulation results | 148 |
| 5.3 | Room temperature payload prototype | 151 |
| 5.3.1 | OSEM characterization | 153 |

| | |
|--|------------|
| 5.3.2 Inertial damping of the optic stage | 154 |
| 5.3.3 Inertial damping of the intermediate stage | 157 |
| Conclusion | 159 |
| Conclusions | 159 |
| Recommendations and future work | 161 |
| A Test facility and Advanced Virgo MultiSAS | 165 |
| A.1 Inverted pendulum transfer function | 166 |
| A.2 Resonance modeling and measurements | 167 |
| A.3 Tuning methods | 170 |
| A.4 Local coordinate systems at Virgo | 171 |
| A.5 Control in Advanced Virgo systems | 173 |
| B Interferometric readout in fiber for CLiC | 175 |
| B.1 Fiber test set-up fabrication | 176 |
| B.2 Results of the prototype set-up | 177 |
| Bibliography | 179 |
| Summary | 193 |
| Samenvatting - summary in Dutch | 201 |
| Riassunto - summary in Italian | 209 |